The CERES/ARM/GEWEX Experiment (CAGEX) for the Retrieval of Radiative Fluxes with Satellite Data

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ABSTRACT

Results from a temporally intensive, limited area, radiative transfer model experiment are on-line for investigating the vertical profile of shortwave and longwave radiative fluxes from the surface to the top of the atmosphere (TOA). The CERES/ARM/GEWEX Experiment (CAGEX) Version 1 provides a record of fluxes that have been computed with a radiative transfer code; the atmospheric sounding, aerosol, and satellite-retrieved cloud data on which the computations have been based; and surface-based measurements of radiative fluxes and cloud properties from ARM for comparison.

The computed broadband fluxes at TOA show considerable scatter when compared with fluxes that are inferred empirically from narrowband operational satellite data. At the surface, LW fluxes computed with an alternate sounding dataset compare well with pyrgeometer measurements. In agreement with earlier work, the authors find that the calculated SW surface insolation is larger than the measurements for clear-sky and total-sky conditions.

This experiment has been developed to test retrievals of radiative fluxes and the associated forcings by clouds, aerosols, surface properties, and water vapor. Collaboration is sought; the goal is to extend the domain of meteorological conditions for which such retrievals can be done accurately. CAGEX Version 1 covers April 1994. Subsequent versions will (a) at first span the same limited geographical area with data from October 1995, (b) then expand to cover a significant fraction of the GEWEX Continental-Scale International Project region for April 1996 through September 1996, and (c) eventually be used in a more advanced form to validate CERES.

1. Introduction

The basic energy drive of the climate system is the spatial and temporal displacement of the absorption of broadband shortwave (SW; solar) radiation and the corresponding equivalent emission of broadband longwave (LW; thermal infrared) radiation. The surface and atmospheric radiation budget (SARB) consists of the time series of the vertical profiles of SW and LW fluxes. Increasing concentrations of radiatively active trace gases are expected to force secular changes in the vertical profiles of fluxes, producing a warmer troposphere and cooler stratosphere. Anthropogenic aerosols effect the climate by altering the profiles of radiative fluxes. While GCMs calculate the full vertical profiles of SW and LW fluxes, the profiles are not routinely measured. Measurements of broadband radiative fluxes have been made at the top of the atmosphere (TOA) by satellites extensively, but not continuously; at the surface, there are a limited number of well-calibrated stations. An observationally based record of the full profile of radiative fluxes is needed to investigate the role of radiation in hydrological and meteorological processes; to determine the forcings of clouds, aerosols, and changing surface optical properties; and to validate GCMs. In GCMs, uncertainties in the simulation of the SARB translate directly into uncertainties in the simulation for climate. The advancement of techniques for retrieving the SARB with satellite data is a goal of the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP).

Confidence in a retrieval of the full profile of the SARB is limited by issues concerning (a) the tech-

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In final form 4 June 1996.

nique applied for broadband radiative transfer, (b) the input data used in the retrieval, and (c) the measurements available for validation. Regarding formal radiative transfer (a), we note the efforts of the Intercomparison of Radiation Codes in Climate Models (ICRCCM; Ellingson and Fouquart 1990; Ellingson et al. 1991) and the Spectral Radiation Experiment (SPECTRE; Ellingson and Wiscombe 1996) to test and advance techniques. Significant problems in atmospheric radiative transfer remain, however, even for some of the most ubiquitous conditions. For example, in the case of surface SW insolation for clear skies, the fluxes calculated with widely used GCM codes are significantly biased when compared with measurements (Wild et al. 1995). In retrievals of flux profiles with cloudy skies, the input data used in the retrieval (b) can easily be misinterpreted (i.e., Wielicki and Parker 1992). The input data on cloud optical properties are dependent on the validity of radiative transfer again, but here in the narrow bands of the satellite radiometer. It is a further challenge to obtain satisfactory calibration for the satellite instrument itself (i.e., Brest and Rossow 1992). To validate a retrieval of the SARB within the atmosphere (c), there are only a few measurements of radiative fluxes by aircraft. In addition, natural meteorological variability poses a formidable barrier to the interpretation of any record of the vertical profile of radiative fluxes that is available for validating a retrieval. For example, Hayasaka et al. (1995) have shown how readily the multidimensional effects of clouds can confuse the absorption inferred from a simultaneous record of SW fluxes at two different flight levels. It is quite difficult to produce accurate measurements of radiative flux divergence.

In an attempt to address these and related difficulties, we have placed a virtual cage over a small area that is well instrumented and begun a long-term, collaborative effort to calculate, observe, and interpret the broadband SW and LW fluxes that drive the physics of climate (Fig. 1). The cooperative CERES/ARM/GEWEX Experiment (CAGEX) is a public access set of input data, calculated fluxes, and measurements over the Department of Energy Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma. Version 1 of CAGEX uses a 3 by 3 grid (0.3° on each side) every 30 min from 1409 UTC to 2239 UTC (daylight) for 26 days, starting on 5 April 1994. CAGEX Version 1 now provides on-line access (see appendix) to

1) satellite-based cloud properties and atmospheric sounding data that fulfill input requirements for calculations with broadband radiative transfer models,
2) vertical profiles of radiative fluxes calculated with those data as input, and
3) measurements of broadband radiative fluxes and cloud properties for comparison with some of the flux calculations and input data.

Successive versions of CAGEX will revisit the same area and seek advances in the quality of the cloud, aerosol, sounding and surface optical property data, the calculated fluxes, and the measurements of fluxes and atmospheric radiative properties. Additional measurements from the expanding array at the ARM SGP site will be included.

CAGEX is used in prelaunch tests of algorithms for the retrieval of the vertical profile of SW and LW fluxes in the NASA Clouds and the Earth's Radiant Energy System (CERES) program. CERES (Wielicki and Barkstrom 1991) is a follow-on to the measurement of broadband TOA fluxes in the Earth Radiation Budget Experiment (ERBE; Barkstrom et al. 1989; Harrison et al. 1990). CERES will also simultaneously retrieve cloud properties with satellite imager data (Wielicki et al. 1995): the Visible Infrared Scanner imager (similar to the Advanced Very High Resolution Radiometer) on the Tropical Rainfall Measurement Mission for 1997 launch and Moderate-Resolution Imaging Spectrometer on the Earth Observing System AM platform for 1998 launch. The calculation of the SARB, consistent with the measured broadband TOA fluxes and cloud property retrievals, will be a small component of CERES (Charlock et al. 1994a).

CAGEX is a gateway providing the atmospheric sciences community with access to current CERES research on the SARB. With the present generation of satellite sensors and broadband radiative transfer codes, the full profile of the SARB cannot be determined with sufficient accuracy in many cases. CERES aims to (a) extend the domain over which the SARB can be determined accurately, (b) quantify the uncertainty in other areas, and (c) use a comparison of computed and observed broadband TOA fluxes as a diagnostic of both radiative transfer techniques and the CERES satellite-based cloud properties. Pioneering efforts to retrieve the SARB with satellite data have been made (i.e., Stuhlmann et al. 1992; Ellingson et al. 1994); some demonstrate that aspects of the problem may require even more sophisticated active sensors, such as a cloud profiling radar (Charlock et al. 1994b). A mature form of the present experiment will eventually be used for postlaunch validation of CERES products over the ARM CART Southern Great Plains, Tropical West Pacific, and North Slope of Alaska sites.

The remainder of this paper has the following outline. Section 2 discusses the calculation of radiative fluxes in CAGEX, focusing on the data input for the Fu and Liou (1993) radiative transfer code. Section 2 also lists the more important parameters that are available on-line. Section 3 gives examples of CAGEX results, comparing calculations with observations. The examples will be used to illustrate the distinction of the present small effort and the larger ICRCCM and SPECTRE campaigns; ICRCCM is an extensive intercomparison of SW and LW flux codes from broadband to line by line; SPECTRE is now comparing spectral LW measurements with calculations for clear-sky conditions. The plans for subsequent versions of CAGEX in the ARM Enhanced Shortwave Absorption Experiment (ARESE) and the GEWEX Continental-Scale International Project (see Leese 1995) are in section 4. The appendix describes how to access CAGEX Version 1 on-line.

2. Calculation of radiative fluxes

a. Radiative transfer and satellite data

The CAGEX estimate of the full SARB over the ARM CART site is produced by forward radiative transfer calculations and based heavily on satellite data. In this respect, while CAGEX is spatially and temporally intensive, the approach is similar to that used in the global GEWEX Surface Radiation Budget (SRB) Project (Whitlock et al. 1995). The SRB Project uses International Satellite Cloud Climatology Project (Rossow et al. 1991) data and fast SW (Pinker and Laszlo 1992) and LW (Gupta et al. 1992) radiation codes for surface fluxes. Here, full vertical profiles of SW and LW fluxes are calculated with the moderate speed Fu and Liou (1993) δ-four-stream code.

The cloud properties for input to the code are obtained from the half-hourly layered bispectral threshold method (LBTM) retrievals of Minnis et al. (1995), which are based on Geostationary Operational Environmental Satellite (GOES) data (Fig. 1, upper-right panel). The Minnis et al. (1995) cloud retrieval also provides empirical estimates of the broadband TOA albedo and outgoing longwave radiation (OLR), based on narrowband *GOES-7* radiances; the empirical relationships were developed with *GOES-6* and Earth Budget Radiation Satellite data (Minnis et al. 1991). Temperature and humidity soundings were obtained by interpolating data from standard National Weather Service (NWS) radiosondes. TIROS Operational Vertical Sounder (TOVS) temperatures are used above 100 hPa. Ozone was obtained from Solar Backscatter Ultraviolet Experiment (SBUV). For the single grid-box at the ARM Central Facility (CF), CAGEX provides an alternate sounding from the Mesoscale Atmospheric Prediction System (MAPS). Because of uncertainties relating to upper-tropospheric humidity in soundings, we have used a LOWTRAN "climatological" humidity above 300 hPa. The sensing of upper-tropospheric humidity is problematic, and even the climatology in this region is poorly known. ARM plans to address this with an Intensive Observing Period (IOP) dedicated to water vapor.

The CAGEX record of computed fluxes spans 48 vertical levels with a 3 by 3 horizontal array (Fig. 1, lower-left panel). Direct measurements of broadband fluxes are available only at the surface in the central grid-box (Fig. 1, upper-left panel). The Fu–Liou (1993) plane-parallel, δ-four-stream code uses a correlated-*k* treatment (Fu and Liou 1992) of gaseous absorption and emission. The δ-four-stream approach agrees with adding– doubling calculations to within 5% for fluxes and is a considerable improvement over a two-stream calculation (Liou et al. 1988). Scattering is treated in LW, as well as SW. The code accounts for the radiative effects of H_2O, CO_2, O_3, O_2, CH_4, and N_2O; Rayleigh scattering; aerosols; liquid cloud droplets; hexagonal ice crystals; and spectrally dependent surface reflectivity. Six spectral intervals are used in the SW (0.2–4.0 μm); 12 spectral intervals are used in the LW (2200–1 cm^{-1}). Continuum absorption of H_2O (Roberts et al. 1976) is included (280–1250 cm^{-1}). The uniform mixing ratios for CO_2, CH_4, and N_2O are, respectively, 330, 1.6, and 0.28 ppmv; mixing ratios in 1994 were larger, but the total difference in the forcing with 1994 concentrations would amount to less than 1 W m^{-2}. CFCs are also not included in the calculation, but CFC forcing is also less than 1 W m^{-2}. For the principal atmospheric gases, the Fu–Liou (1993) code matches a line by line simulation of fluxes to within 0.05% for SW; 0.2% for LW, excepting O_3; and ~2% for LW fluxes due to O_3. An updated line database is not expected to change results very substantially. Q. Fu and K.-N. Liou (1996, personal communication) are planning a version with updated line parameters. It should be noted,

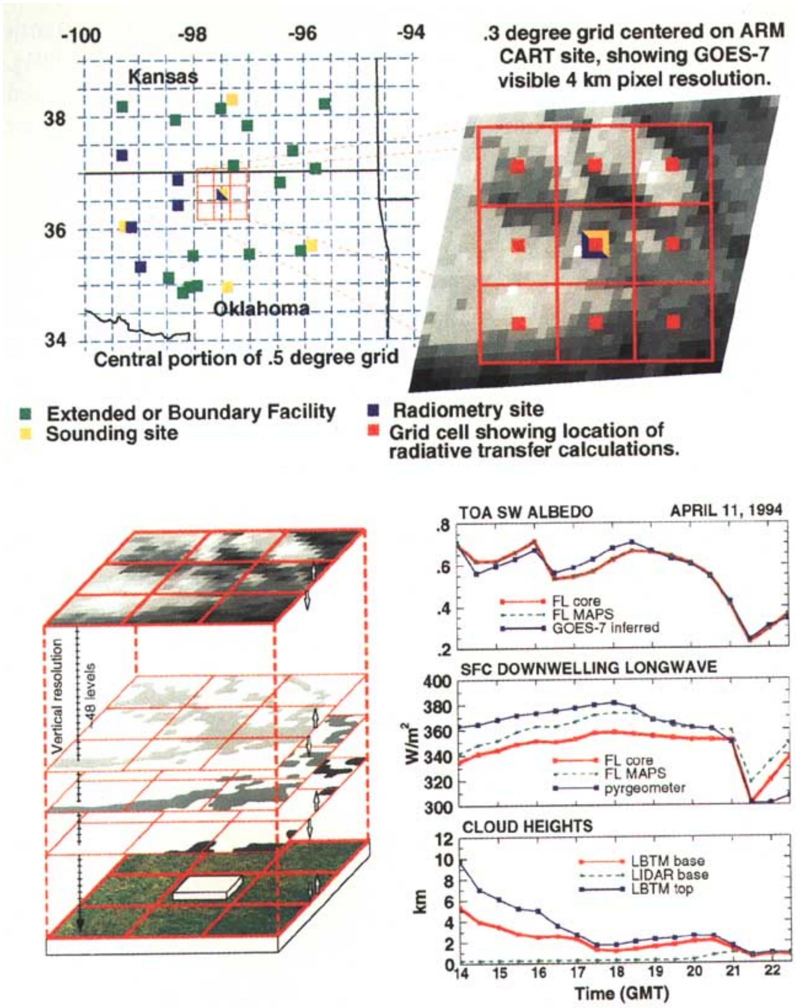

FIG. 1. The CERES/ARM/GEWEX Experiment (CAGEX). Upper left: Map of CAGEX horizontal 3 by 3 grid with ARM surface facilities. Lower left: 3D depiction of 48 vertical levels with 3 by 3 horizontal grid. Upper right: *GOES-7* pixels (Minnis et al. 1995) in 3 by 3 horizontal grid. Lower right: Time series of calculated (FL core and FL MAPS) and observed (GOES-inferred) albedo at TOA; calculated (FL core and FL MAPS) and observed (pyrgeometer) surface downward longwave flux; satellite-retrieved (LBTM) heights of cloud top and cloud base with surface lidar-measured cloud base.

however, that there are significant uncertainties relating to the treatment of the H_2O continuum (i.e., Clough et al. 1992) in radiative transfer codes generally. ICRCCM and SPECTRE are anticipated to provide more definitive evaluations of radiative transfer codes as a guide to their improvement.

The CAGEX flux calculations with the Fu–Liou code use the Minnis et al. (1995) LBTM GOES-based retrievals of cloud amount, cloud temperature, cloud-top height, cloud geometrical thickness, and visible optical depth. Up to three cloud amounts (fractional area of low, middle, and high) are reported in a grid box of 0.3° by 0.3°, but the different cloud types (low, middle, and high) are not assumed to overlap vertically. A future version of CAGEX will use use cloud profiling radar for cloud overlap; Charlock et al. (1994b) has a global estimate of the sensitivity of the LW SARB to different assumptions for cloud overlap. In the present version, cloud temperature is determined from the satellite 10.2–12.2-μm channel radiance. The height of the cloud top is obtained from an atmospheric sounding that is interpolated from the 12-h NWS radiosondes. Cloud geometrical thickness is estimated by the LBTM retrieval using an empirical relationship between geometrical thickness and visible optical depth. The Minnis et al. (1995) visible optical depth is based on a look-up to adding–doubling calculations, which accounts for the distinct phase functions of liquid and ice cloud particles. Clouds with tops having temperatures at 253 K and higher are assumed to have liquid droplets, while those with colder tops are assumed to be ice.

In the broadband flux calculations for clouds with the Fu–Liou (1993) code, we use particle sizes of 10 μm for liquid and 30 μm for ice. The code is driven by cloud liquid water content (LWC in g m^{-3}), which we take as the integrated liquid water path (in g m^{-2}) that corresponds to the particle size and the reported visible optical depth. The cloud LWC is spread homogeneously among the layers that are between the reported cloud top and bottom (inferred from the geometrical thickness).

b. Surface data

Instruments at the Central Facility of the ARM SGP CART site (Stokes and Schwartz 1994) are essential to CAGEX Version 1. The optical properties of the surface and of aerosols in the forward flux calculations with the Fu–Liou code are taken partly from these measurements. Other ARM measurements are used diagnostically. The Spinhirne (1993) MicroPulse Lidar (MPL), which is accurate from the surface to the lower stratosphere, measures the altitude of the lowest cloud base above the CF. The CAGEX on-line files include the air temperature and humidity as measured at 2 m and at a 60-m tower.

The integrated aerosol optical thickness for the full atmospheric column in 5 SW channels is obtained from the Multi Filter Rotating Shadowband Radiometer (MFRSR) spectral measurement of the direct and diffuse solar beam at the surface, as processed by the narrowband retrieval algorithm of Harrison et al. (1994). For the broadband Fu–Liou radiative transfer calculation, we estimated aerosol optical thickness in the near and thermal infrared by scaling the MFRSR values at shorter wavelengths using the humidity-dependent tables of d'Almeida et al. (1991). The d'Almeida et al. tables for continental aerosol are used to estimate the aerosol single-scattering albedo and asymmetry parameter at all wavelengths. Aerosols were apportioned with altitude using a distribution that was originally developed from an oceanwide survey of airborne lidar data (Spinhirne 1991). CAGEX Version 1 calculations used a preliminary MFRSR record of aerosol optical depth that J. Michalsky (1996, personal communication) advises to be in error by ~0.01 (roughly 5%–10% of the usual aerosol optical depth). Based on sensitivity calculations to doubled aerosol optical depth, this error should have a very small effect on the calculated flux.

Broadband pyranometers and pyrgeometers (i.e., DeLuisi 1991), operated as in the Baseline Surface Radiation Network (BSRN; Gilgen et al. 1993), provide near-surface upwelling and downwelling SW and LW fluxes. A pyrheliometer is used for the direct SW beam, and a shaded pyranometer gives the downwelling diffuse SW. To determine the surface spectral reflectance for the six SW channels in calculations with the Fu–Liou code, we first calculate a broadband surface albedo from the flux records of the unshaded uplooking and downlooking broadband pyranometers. This measured broadband albedo was then apportioned to the six SW channels using the reported shape of spectral reflectance in a short grass meadow (Briegleb et al. 1986). For a given radiative transfer calculation, we assume the same spectral reflectance at the surface for the downwelling direct and diffuse beams.

3. Examples of CAGEX results

a. SW fluxes

The "core" soundings, which are based on interpolations from 12-h radiosonde data, are used for calculations over the 3 by 3 horizontal array of CAGEX. Over the central grid box, alternate soundings based on the 3-h MAPS and our corresponding set of calculated fluxes are also available on-line. ARM surface measurements correspond to the central grid box. Table 1 shows the mean biases of SW flux for the available intersections of observations and calculations, from 18 half-hourly calculations during each of the 26 days of Version 1 (the lower-right panel of Fig. 1 has sample time series for a single day). The respective mean incoming TOA insolations are given in Table 1. The mean TOA insolations in Table 1 differ because clear-sky conditions are only a subset of the total-sky domain; core soundings and MAPS soundings were missing for different time steps in the 26-day sample.

Both the core and MAPS soundings produce mean TOA albedos with the Fu–Liou code that are quite close to observed LBTM albedos of Minnis et al. (1995) for clear skies. Total-sky conditions include the effects of clouds, and then the calculations have a negative bias for SW TOA net flux; that is, the entry of −15 W m^{-2} in Table 1 indicates that the TOA ab-

TABLE 1. Biases (calculated–observed in W m^{-2}) of SW flux in CAGEX.

	Total-sky SW		Clear-sky SW	
Sounding: (TOA insolation)	**Core (971)**	**MAPS (985)**	**Core (962)**	**MAPS (961)**
TOA net	−15	−14	−3	−5
Atmospheric absorption	−58	−53	−33	−33
Surface net	43	39	29	28
Surface down	49	42	35	32
Surface direct down	−24	−34	32	22
Surface diffuse down	76	78	8	11

sorption inferred empirically from the satellite (the LBTM empirical conversion of narrowband *GOES-7* radiance to broadband flux) is larger than that calculated by the code (Fu–Liou radiative transfer with LBTM cloud properties for input). A plot comparing observed and calculated total-sky albedo displays significant scatter throughout its range (Fig. 1a). An observational value for atmospheric absorption is produced by differencing the satellite TOA flux (an average over the grid box) with the surface net flux measured radiometrically at the ARM SGP Central Facility (a point). Table 1 shows that the Fu–Liou calculated atmospheric absorption (an average over the grid box) is too small for both clear and total skies. The deficiency in calculated absorption is greater for total-sky conditions, wherein the photon pathlength can be longer because of clouds. The separate biases for the direct and diffuse components are quite sensitive to the method applied for cloud screening. This is a topic for further research.

Calculated surface insolation for clear-sky conditions is too large (Fig. 1b), in agreement with Wild et al. (1995). Calculated surface insolation for total-sky conditions is again too large (Fig. 1b), in agreement with the GEWEX SRB Project (Alberta et al. 1994; Whitlock et al. 1995). Each SW bias in Table 1 can be very roughly scaled to an effective annual global, 24-h value by 1) multiplying the bias by the annual global, 24-h TOA insolation (1365/4 W m^{-2}) and then 2) dividing by the corresponding mean TOA insolation of the bias. Table 1 gives the mean TOA insolation for each bias. For example, the bias in total-sky surface downward flux with MAPS is 42 W m^{-2} for a mean TOA insolation of 985 W m^{-2}. This local-scale, daylight CAGEX bias would then be very roughly equivalent an annual global, 24-h bias of 15 W m^{-2}.

b. LW fluxes

A parallel summary for LW is given in Table 2 and Figs. 1c,d. For LW, we consider the TOA observations to be the LBTM empirical conversion of narrowband *GOES-7* to OLR. Surface LW observations are obtained from the pyrgeometers at the ARM CF. As with SW, the Fu–Liou calculations using the 3-h MAPS soundings are generally closer to the observations than are the Fu–Liou calculations with core soundings from interpolations of 12-h NWS radiosondes. MAPS results are featured in the scatter plot (Figs. 2c,d). The bottom rows of Table 2 show that for the core sounding the interpolated temperature field is not adequate for calculating LW surface fluxes. However, the 12 W m^{-2} excess for clear-sky OLR calculated with the MAPS sounding is substantial. The total-sky bias becomes slightly negative at low values of OLR (Fig. 2c). Conditions of intermediate OLR are associated with intermediate conditions of cloud cover (partial sky cover, thin but overlapping clouds, etc.), which challenge satellite-based retrievals of cloud properties; as expected, the scatter in Fig. 2c is large for intermediate OLR. The small bias and scatter in the observed versus computed surface downward LW flux attest to the surprising fidelity of the surface LW cloud forcing inferred from the Minnis et al. (1995) LBTM retrievals of cloud areal coverage and altitude of cloud base (Fig. 2d). The retrieval of the altitude of cloud base (bottom) with data from passive satellite sensors has been regarded as a challenge.

4. Discussion

a. Comments on results

The comparison of calculated and observations fluxes in Tables 1 and 2 and Figs. 2a–d shows significant discrepancies. For surface SW flux, the discrepancies are larger than the uncertainties in the radiometric measurements, as found in earlier studies [i.e., Whitlock et al. (1995) using algorithms from Darnell et al. (1992) and Pinker and Laszlo (1992)]. For the observations of surface SW insolation, we combined measurements of the direct pyrheliometric flux and the diffuse flux from a shaded pyranometer, as recommended by BSRN. More SW atmospheric absorption is needed in the simulation for both clear-sky and total-sky conditions.

For clear skies the core and MAPS soundings,

TABLE 2. Biases (calculated–observed in W m^{-2}) of LW flux in CAGEX.

	Total-sky LW		Clear-sky LW	
Sounding:	Core	MAPS	Core	MAPS
OLR	2	5	4	12
Surface net	3	1	7	−5
Surface down	−9	1	−17	−6
Surface up	−12	−1	−25	−2

which have different water vapor loadings (mean precipitable water of 1.64 cm for core and 1.85 cm for MAPS), give similar errors for SW radiative flux. The solution to the problem of clear-sky insolation is not likely in the water vapor sounding. The surface optical properties, here specified from ARM radiometers at a single point, have only a small impact on insolation. Hence, we suspect a problem with either the simulation of the optical properties of the gases and/or a simulation or measurement of the optical properties of aerosols. For clear skies, we must recall that ICRCCM, an extensive intercomparison of SW and LW flux codes from broadband to line by line, also shows disagreements between codes; the disagreements have not been fully diagnosed. A rigorous spectral comparison of atmospheric codes and simulations under highly defined conditions is needed, and efforts are under way within the SPECTRE (Ellingson and Wiscombe 1995) and ARM (Stokes and Schwartz 1994) programs. An improvement in the calibration of the ARM broadband radiometers is a key requirement. The Direct Aerosol Radiative Forcing (J. Ogren 1995, personal communication; see IGAC 1995) initiative and earlier reviews (i.e., Penner et al. 1994) indicate that the satisfactory measurement of aerosol radiative properties will indeed be a challenge, especially as regards absorption. It should be noted that the present report of a discrepancy between calculations and measurements for clear-sky insolation is not universal; Chou and Zhao (1996) and Waliser et al. (1996) find that calculations and measurements agree in the tropical Pacific.

For total-sky SW fluxes, we cannot diagnose our errors as well as for clear skies. The reflected component is more important with clouds, and it is difficult to accurately measure broadband TOA reflected flux using a narrowband radiance such as *GOES-7*. As noted earlier, the calibration of narrowband radiometers on operational satellites can be problematic (Brest and Rossow 1992; Whitlock et al. 1995). After calibration, the measured directional radiance must be converted to a flux using angular and directional models (i.e., Suttles et al. 1988; Suttles et al. 1989). Scene identification is important because the angular distribution of radiation is influenced by the surface and by clouds [note the procedure of Wielicki and Green (1989), which was used in ERBE]. The narrowband measurement must be spectrally transformed to broad band (Minnis et al. 1991). Each step is a source of error. We should hence not be sanguine about the small biases for SW TOA fluxes in Table 1. There may be compensating errors.

The large biases in total-sky atmospheric absorption (Table 1) indicate a problem with our SW calculations for cloudy skies. While we included the indirect effect of aerosol absorption (Twomey 1977) in the SW calculations, the aerosol that is enveloped by cloud was only crudely estimated from the total-column aerosol optical depth measured in clear skies, a climatological aerosol height distribution, and the satellite-retrieved altitudes of cloud top and cloud

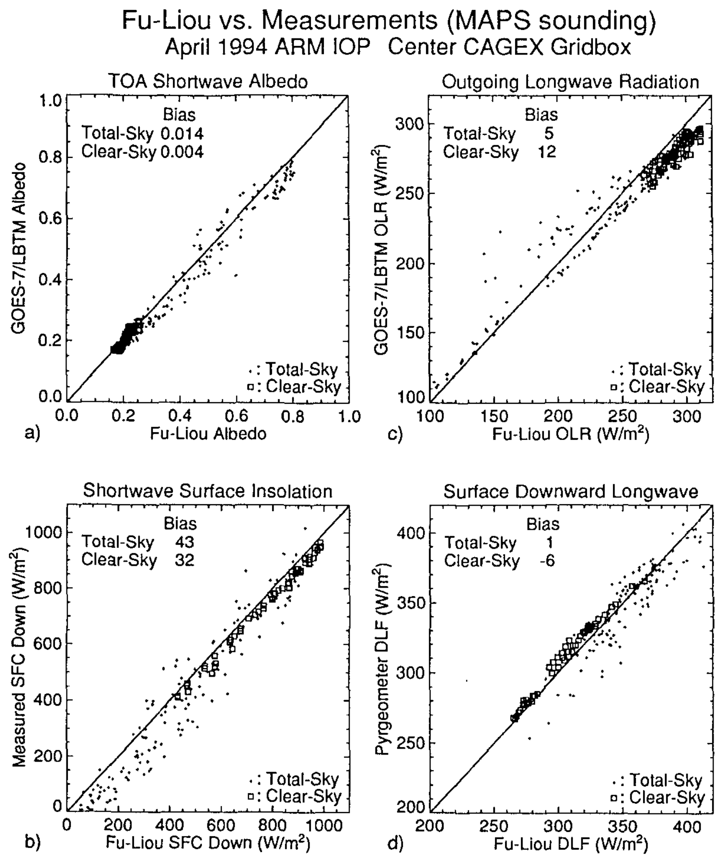

FIG. 2. Calculations with Fu–Liou code, satellite-retrieved clouds, and MAPS soundings compared with observations for clear-sky and total-sky conditions: (a) TOA shortwave albedo, (b) SW surface insolation, (c) outgoing longwave radiation, and (d) surface downward longwave.

base. Stephens and Tsay (1990) have reviewed more general cases wherein clouds appear to absorb more SW than simulated by the codes; this issue remains unresolved (Li et al. 1995; Hayasaka et al. 1995; Chou et al. 1995; Ramaswamy and Friedenreich 1992). Ice clouds pose an especially formidable challenge, both in terms of theory (Liou 1992) and remote sensing (Minnis et al. 1993a,b). Our calculations and satellite-based cloud retrievals use the plane-parallel assumption, which is expected to cause systematic errors in optical property retrieval [i.e., note the "independent pixel" problem in Cahalan et al. (1994)]. An error in the optical property retrieval would translate to an error in calculated flux.

The CAGEX biases for LW fluxes appear to be more straightforward than for SW. In LW, a shift to the more time-intensive MAPS soundings as input for the radiative transfer code generally improved the match of calculations and observations. At both the TOA and at the surface, the comparison of clear-sky calculations with observations suggests that the real atmosphere is more opaque than the modeled atmosphere; the clear-sky OLR calculated by the Fu–Liou code with the MAPS soundings exceeds the LBTM observation by 12 W m^{-2}; the corresponding clear-sky surface downward LW is 6 W m^{-2} smaller than the observations. Is this due to the water vapor continuum? A more opaque continuum would be more likely to affect the flux at the surface (error magnitude only 6 W m^{-2}) rather than at the TOA (error magnitude 12 W m^{-2}). The OLR error could be caused by an error in the sounding at high altitude, the radiative transfer code, a misrepresentation of the surface temperature or emissivity at the CF (i.e., the CF may not represent the whole grid box adequately), or the OLR observation itself. Collins and Inamdar (1995) have noted significant sources of error when inferring clear-sky OLR, even from a specialized broadband instrument such as ERBE.

b. Plans

CAGEX will be continued beyond the April 1994 domain of Version 1. CAGEX Version 2 will cover the ARM Enhanced SW Experiment (25 September 1995–1 November 1995). ARESE targets the absorption of SW radiation by the troposphere under both clear and cloudy conditions. A unique aspect of ARESE is the measurement of broadband SW fluxes by 3 aircraft (a Twin Otter below 2 km, an Egret at 13 km, and an ER-2 at 20 km). We will include surface radiometric measurements that were made at several sites and also plan to include aircraft-measured fluxes. Airborne measurements were made for a fraction of ARESE, but the CAGEX calculations will be extended to 24 h day^{-1}. Soundings will be obtained from two sources, the special cluster of 3-h ARM radiosonde launches and the National Center for Environmental Prediction mesoscale Eta model output (Yarosh et al. 1996, manuscript submitted to *J. Geophys. Res.*). We plan to use water vapor retrievals from a surface-based microwave radiometer and from the Atmospheric Emitted Radiance Interferometer (Revercomb et al. 1993). The water vapor profiles will be further studied, and perhaps adjusted, with surface-based Raman lidar (Melfi et al. 1989) and 6.7-μm satellite soundings (Soden et al. 1994). Data from the upcoming ARM water vapor IOP will not be available for CAGEX Version 2, but our high-altitude water vapor climatology will be improved with Stratospheric Aerosol and Gas Experiment data. Minnis et al. (1995) intend to provide histogram statistics of the pixel-scale satellite radiances and cloud properties within each 0.3° by 0.3° grid box. Spinhirne (1993) intends to provide elementary information on the distribution of aerosol extinction with altitude from the MPL, in addition to the current measurement of cloud-base height. Lacking further data on aerosol absorption, CAGEX Version 2 will continue with the d'Almeida et al. (1991) climatology. A comparison of the radiative diabatic heating profiles from CAGEX and the eta model will be made available.

An expanded area, 0.5° by 0.5° run of CAGEX Version 3 will cover April 1996 continuously through September 1996 for GCIP. Accuracy will not be as great as in the immediate vicinity of the ARM SGP CART site, which will retain a concentration of data and effort. NOAA surface radiation (Hicks et al. 1995) will provide measurements of aerosol optical depth and surface fluxes at other sites. CERES plans to conduct a surface optical property experiment over the SGP site during 1997, measuring the surface SW broadband albedo, SW spectral bidirectional reflectance, and the angular dependence of LW window radiance with a helicopter (Whitlock et al. 1994); a preparatory airborne experiment has been conducted over Virginia to support this. The survey of surface radiative characteristics in the First International Satellite Land Climatology Project Field Experiment (FIFE; Sellers and Hall 1992) provides impetus to take similar measurements over the SGP site. These measurements will be used in tests of CERES algorithms for retrievals of the SARB.

We advocate CAGEX as a useful complement, regularly spanning a grid for many time steps, to the more focused but smaller domain activities planned by SPECTRE. CAGEX is a test of the remote sensing of the spatial and temporal variations in broadband flux, as well as instantaneous radiative transfer. The radiative "noise" induced by a rapidly changing 3D cloud field can be enormous. An integrating experiment is needed to establish accuracy bounds for present means of determining radiative flux. The experiment should be repeated in the same local area as new measurements become available. We invite collaboration.

Acknowledgments. We were assisted by several colleagues, both at NASA/Langley and throughout the atmospheric sciences community, in the development of CAGEX. The experiment is largely a means of accessing their research. Patrick Minnis (NASA/Langley) and William Smith Jr. (Analytical Services and Materials, Inc.; hereafter AS&M) released their satellite cloud and TOA products, and answered endless questions about them. Qiang Fu (Dalhousie University) and Kuo-Nan Liou (University of Utah) supplied us with the δ-four-stream code and modified it to include a treatment of aerosols. John DeLuisi and Trevor Ley (NOAA/ARL in Boulder, Colorado) provided radiometric data from the ARM site and many comments on those data. James D. Spinhirne (NASA/Goddard Spaceflight Center) provided his MPL cloud-base height data and consulted on the application of his 1991 aerosol height profile model. Fred G. Rose (AS&M) guided many of the calculations and manipulations of datasets. David Rutan (AS&M) developed a surface spectral reflectance algorithm and made narrowband radiative transfer calculations. Shi-Keng Yang and Ron Nagatani (NCEP) provided TOVS upper-level soundings, SBUV ozone profiles, and guidance on the manipulation of sounding data. Joseph Michalsky (SUNY at Albany) was a source of advice on the MFRSR retrievals of aerosol optical thickness. Henry Leighton (McGill University), Rolf Stuhlmann (GKSS), Shashi Gupta (AS&M), and Jean-Jacques Morcrette (ECMWF) commented on their application of CAGEX files in radiative transfer calculations. Ming-Dah Chou (NASA/Goddard) provided a version of his SW radiative transfer code, which was used in testing CAGEX.

We have operated under an umbrella of support from CERES PIs Bruce Wielicki and Bruce Barkstrom at NASA/Langley and from Program Manager Robert Curran at NASA Headquarters. Peter Minnet (University of Miami) is our official data representative with ARM. The interest of Gerry Stokes (ARM), Ted Cress (ARM), John Vitko (ARM UAV), and the diplomatic efforts of David Randall (CSU) are appreciated. Prompting by Paul Try (GEWEX), John Leese (GCIP), and Robert Schiffer (NASA Headquarters) helped to orient this experiment toward a wider scientific community.

This manuscript was substantially improved by the thoughtful reviews of David Kratz and Ann Carlson, as well as by the editing of Jennifer Hubble (NASA/Langley). We are grateful to Thomas Ackerman (Penn State), Bruce Barkstrom, and Qiang Fu for further discussions on radiative transfer. After those discussions, two rows in Table 1 and two sentances of text were replaced as this paper was in press.

Appendix: FTP access to CAGEX datasets

The dataset may be accessed on the CAGEX home page:

http://snowdog.larc.nasa.gov:8081/cagex.html

To access CAGEX by FTP:

ftp snowdog.larc.nasa.gov
username: anonymous
password: your complete e-mail address
cd pub
cd CAGEX
get CAGEX.update

The ASCII file "CAGEX.update" contains instructions for obtaining the most current version of CAGEX as either 1) a compressed tar file or 2) a set of files for individual days (if the compressed tar file is too large to transfer).

This paper documents CAGEX Version 1.0. A subsequent version, 1.1, which revisits April 1994, is planned for release in mid-October 1996. Plans for Versions 2 and 3 are described in the text.

Postscript versions of the HTML files are available in pub/CAGEX. These presently include

- description.ps (an overview of CAGEX)
- data_description.ps (about the CAGEX data)
- documentation.ps (how data was manipulated in space and time)
- grid_system.ps (an in-depth description of the CAGEX cage).

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